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Review Article

Optical Network Technologies for Future Digital Cinema

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Digital technology has transformed the information flow and support infrastructure for numerous application domains, such as cellular communications. Cinematography, traditionally, a film based medium, has embraced digital technology leading to innovative transformations in its work flow. Digital cinema supports transmission of high resolution content enabled by the latest advancements in optical communications and video compression. In this paper we provide a survey of the optical network technologies for supporting this bandwidth intensive traffic class. We also highlight the significance and benefits of the state of the art in optical technologies that support the digital cinema work flow.

1. Introduction

The transformation to digital cinema is taking place through advancements in optical communications technologies and is accelerated by the gradually decreasing costs. Digital technologies enable communication and storage of digital data without any degradation and at much reduced cost promoting new opportunities. In contrast 35 mm film that dominated the industry for many decades is far from a perfect medium and requires special handling [1, 2]. In 2003, digital high definition (HD) recording was demonstrated for the cinema work flow [2]. HD video has a pixel resolution of 1920 × 1080 and although still prevalent in many devices higher pixel resolutions have become possible. Super HD (4K) with a resolution of 4096 × 2160 pixels has the same image quality as that of 35 mm film [3]. With digital technology the same content produced for cinema can be adapted for TV and mobile device viewing. This content adaptation enables "encode-once, decode-many" process powered through the scalability features [4, 5] in the latest video coding standards.

Majority of the cinema screens worldwide have been digitised driving the need for a digital cinema work flow. Real-time data, that is, audio and video, has strict timing constraints for playback. The video streaming requires a lot of bandwidth to preserve the delay constraints imposed by its real-time nature. The data generated by a single frame in ultrahigh definition (UHD) format is enormous and cannot be supported over today's Internet infrastructure. Although digital cinema content can be moved (on hard disks and other storage media) and stored at movie theatre ahead of show timings, development of live streaming architecture is important as cinema projection facilities can then also be used for live coverage of operas and sports events [6].

The streaming of digital movies requires a communication architecture which supports high data rates in real or near-real time from a local distribution centre to the movie theatre. Such architecture would comprise an all-optical or a combination of optical and existing Gigabit Ethernet. Architectures supporting digital cinema content have been reported in the literature but the increasing viewers' expectations drive and necessitate further advancements [7]. The cinema content will soon move beyond frame resolutions over 4K, frame rates over 24 frames, and bits per sample over 12 bits and from 2D to multiple video streams for multiview video (MVV) for 3D.

The mobile technology revolution is also driving the widespread use of innovative technologies. It enables amateur video producers of short movies in 4K and this trend is likely to increase [8]. 3D cameras [9] are a reality and the depth

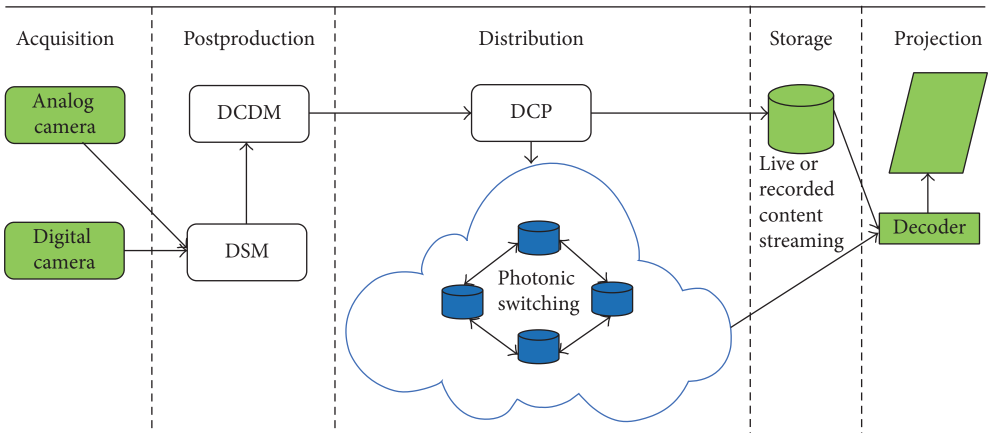

Figure 1: Digital cinema work flow.

information together with advances in image processing and animation techniques open an exciting world of possibilities.

This paper provides a survey of the optical networking technologies for supporting the digital cinema content and gives insights into the use of emerging technologies from optical communications.

The rest of the paper is structured as follows. Section 2 provides an overview of the cinematography process. The video requirements are described in Section 3. Section 4 provides survey of the optical network technologies. Section 5 discusses emerging optical communication technologies to meet the challenges of supporting multimedia data. Finally, Section 6 concludes the paper.

2. Digital Cinematography Process

2.1. Digital Cinema Initiatives (DCI). Digital Cinema Initiatives specification [10] is approved by seven major motion picture studios and provides the main objectives. It specifies a store-and-forward non-real-time method of distribution to the theatres ahead of playback. The data transport can be through any (satellite, fibre, and copper) method but must provide a secure environment for content as well as safeguards against corruption of data. It also lists the manufacturers [11] of DCI compliant equipment. The specification includes the work by Society of Motion Picture and Television Engineers (SMPTE) [12]. There are also ISO standards [13] relating to digital cinematography.

2.2. Work Flow. The transition from decades old film to digital technologies however requires a new work flow [4]. Digital cinematography process encompasses the processes of acquisition, packaging, distribution, and projection of multimedia content as shown in Figure 1.

The content is acquired as Digital Source Master (DSM) which is then transformed as Digital Cinema Distribution Master (DCDM). This is further transformed as a Digital Cinema Package (DCP). The DCP is the standard Media Exchange Format (MXF) in which movies are delivered to theatres. The distribution can take various forms such as physical mediums like hard disks and transmission over satellite or broadband or delivered live over optical networks from a distribution centre.

2.3. Digital Cinema Content. The DSM creates many elements such as Film Distribution, Home Video, and Broadcast Masters. DCI specifies the image coding using JPEG2000 [24]. The two supported video resolutions for the content and projection are 2K and 4K (as shown in Table 1), whereas the audio can be uncompressed.

3. Video Requirements for Digital Cinematography

In this section we describe the video requirements for digital cinema applications. Video transport techniques are briefly mentioned along with the advantages of optical communications for bandwidth intensive video content.

3.1. Video Frame Resolutions and Rates. The digital video applications use progressively higher frame resolutions and frame display rates (frames per second) as new technologies emerge to meet the evolving user requirements and to support better viewing experience.

However higher frame resolutions, frame rates, and MVV can result in very high data rates. Video data even when compressed has a very large size and rate. A comparison of the compression achieved by the standard video coding algorithms is provided in Table 1. Digital cinema resolutions are 2K and 4K, the number representing the horizontal pixel count. 4K (UHD) has four times the resolution of HD display. For compressed rate we have assumed a compression ratio of 20 : 1 (as in [19]) with JPEG2000 [24].

3.2. Video Coding Standards. DCI specifies JPEG2000 as the video compression standard; however other video coding standards could also be considered. A comparison between JPEG2000 and H.264 is provided in [25–27] concluding that JPEG2000 provides better performance at high resolutions

Table 1: Video formats and their corresponding data rates at different frame rates and color depths.

Video data	Resolution (pixels)	Pixels per frame (MP)	Frames per second	Bits per color	Data rate (uncompressed)	Data rate (compressed JPEG2000)
Standard definition (SD)	1080 × 720	0.7	24	10	560 Mbps	28 Mbps
High definition (HD)	1920 × 1080	2.0	24	10	1.5 Gbps	74 Mbps
2K	2048 × 1080	2.2	24 or 48	12	1.9/3.8 Gbps	95/190 Mbps
4K (ultrahigh definition)	4096 × 2160	8.8	24	12	7.6 Gbps	380 Mbps
8K (UHD)	7680 × 4320	33	60	12	72 Gbps	3.5 Gbps

for applications such as digital cinema. Similarly, [28] compared lossy and lossless performance of H.264, JPEG2000, and the latest High Efficiency Video Coding (HEVC) and concluded that HEVC performance is consistent over wide bitrates' ranges.

HEVC [29] offers approximately twice the compression compared to H.264/AVC standard at the same data rate. Because of its high compression efficiency it will ease pressure on the global networks [5] and is an enabler for HD content over mobile networks [30]. The scalable version of HEVC, Scalable HEVC (SHVC) [31], has been released promising easier transcoding to different frame resolutions, frame rates, and qualities.

3.3. In-Place Frame Editing and Single Frame Display. Motion JPEG 2000 standard [24] individually encodes each frame of the video sequence in its entirety without dependence on prior or later frame, although it results in higher data rate as interframe redundancies are not removed but enables fast and direct access to each frame for postacquisition editing.

Other state-of-the-art video coding standards, for example, H.264 and HEVC, encode a video sequence on a group of pictures (GOP) basis making image editing cumbersome.

3.4. Digital Rights Management. The transport of digital cinema content over the public networks makes it vulnerable to unauthorised access by the unintended recipients. The digital data makes protection much easier to implement through encryption, making it very difficult to extract the original data.

3.5. Video Transport

3.5.1. Live Streaming versus Download. The video transport can take place over different delivery channels such as WiMAX, satellite, and optical networks or the content could be distributed on storage media (hard drives, CD/DVD, etc.). For network based delivery the content could be delivered for live playback or could be downloaded offline ahead of the scheduled playback time. In download or store-and-forward [10] model the data can be moved in non-real time to the theatre.

3.5.2. Transport Protocols. Video streaming requires intelligent use of transport protocols and error correction schemes. Until recently, Universal Datagram Protocol (UDP) has been the favoured protocol compared to Transport Control Protocol (TCP) for video streaming. With high speed networks streaming can take place over TCP with guaranteed delivery of data. However, this can result in costly packet loss recovery mechanisms that require modifications to TCP behaviour [32].

3.5.3. Optical Networks. The download time of video content over wireless, satellite, or Ethernet becomes prohibitive for higher resolutions and MVV. Architectures have been proposed based on satellite content delivery networks (CDN) but it would take about 11.5 hrs to download a film of 100 GB [1]. Content distribution through satellite thus may not be suitable for the enormous content at higher resolutions/frame rates. The higher bandwidth capacities could cater for 3D cinematography [33] and lasers as projection light source [34] with even higher rates.

4. Survey of Optical Network Technologies

In this section we describe a survey of the innovations in the optical networks and associated domains. These innovations are the enablers for supporting future innovations in digital content beyond the current state of the art. We provide a survey of the technologies reported in the literature to support digital cinema content distribution over optical networks. For a summary please refer to Table 2.

4.1. Modification to TCP Protocol. A system for SHD digital cinema distribution is implemented in [15], demonstrating live streaming of SHD video at a data rate of 300 Mbps over a distance of 3000 km. The system comprised JPEG2000 real-time decoder, SHD projector, and a movie server. The hardware JPEG2000 decoder was developed to parallel-process the compressed video data. The distribution of SHD content was over TCP/IP over a long distance. The difficulties experienced in case of packet losses due to the error recovery mechanism of TCP were alleviated using spooling the received data stream for 4–8 s in memory. The required data rates (300 Mbps) were achieved by utilizing an enlarged TCP

Table 2: Summary of techniques and technologies for digital cinema content distribution.

Video data	Techniques and technologies	Data rate	Ref
HD/SHD	Data and control support, 10 G Ethernet, large TCP window, multiple TCP, traffic shaping, MPLS	<500 Mbps	[14–17]
4K	IP multicast, FEC, non-real time content distribution	500 Mbps–1 Gbps	[3, 18]
4K/3D, UHD	Lambda, OBS, OTDM, burst switching, jumbo frames, multiple channels	>1 Gbps	[19–23]

window (4 MB), multiple concurrent TCP connections (64), and traffic shaping function to control the data transmission quality and bursty nature. The authors also describe the developed system in some detail in [16], utilizing the same test-bed and achieving transmission speed of 500 Mbps.

4.2. IP Multicast. The applications of super HD image transmission in digital cinema and other application fields are discussed in [3]. The paper proposed a digital delivery system that can deliver 4K cinema content in timely manner through optical networks using IP multicast. The proposed system can compress/decompress 4K videos, achieving uncompressed bit rate of 12 Gbps (60 fps) and compressed streams at 500–1000 Mbps. Forward Error Correction (FEC) based on Low Density Generator Matrix (LDGM) is proposed realising error-free video streaming on networks with 0.5% average packet loss rate. The paper discussed how the same infrastructure can be used for remote collaboration through IP multicast group.

4.3. Architecture Supporting Data and Control. An acquisition infrastructure based on 10 G Ethernet is proposed in [14]. The optical Ethernet technology can support bidirectional long distance networking. The paper demonstrated overcoming the limitations of audio/video streaming interfaces through the use of solid state based recording systems combined with 10 G Ethernet based interfacing. The real-time behaviour is guaranteed through an architectural split into different blocks for supporting real-time data transport and control messages. The proposed architecture supports HD video.

4.4. Multiprotocol Label Switching (MPLS). The work described in [17] for EDCINE project presented key issues relating to digital cinema content using IP multicast transmission networks. Unlike DCI specification, live streaming is also considered together with Quality-of-Service (QoS) constraints of end-to-end delay, packet loss rate, and delay jitter while keeping the overall management cost low. This required resource reservation and traffic engineering (TE) over MPLS networks. For this purpose, an extension of RSVP protocol (RSVP-TE) has been adopted. The prerecorded content could be downloaded from CDNs to the movie theatres over wired or wireless channels without the need of IP multicast but live content distribution required IP multicast service. The paper also described mathematical models for the optimisation of prerecorded movies and delivery of live events.

4.5. Lambda-Switched Services. The advantages and challenges for deployment of dynamic all-optical multicast network for supporting SHD and UHD applications are discussed in [19]. The test-bed High Performance Networked Media Laboratory including optical and video technologies is developed and utilized. It considers both uncompressed and compressed single streams and MVV with JPEG2000. The authors highlighted multiple issues such as the dynamic allocation of network resources, including light-paths, signalling for services, multicasting, dynamic integration of L1, L2, and L3 operations, device addressing, and new mechanisms for network management and control. High performance optical networks comprised photonic switching with Generalized MPLS that has the capability to support UHD digital media distribution. Further, the paper described the suitability of Lambda-switched services for UHD media services for long-lived flows; Optical Burst Switching (OBS), an optical network technology that allows dynamic subwavelength switching of data to improve the use of optical networks resources for flows not requiring resource reservation for long periods, and Optical Time Division Multiplexing (OTDM) technology multiplex a number of low bit rate optical channels in time domain for uncompressed SHD/UHD MVV applications.

4.6. Burst Switching. Burst switching for supporting diverse and dynamic traffic is discussed in [20]. The paper described the requirements for digital media services and innovations in the optical networking. The techniques are described in the context of two application areas of (1) high resolution visualisation in science and (2) high-quality real-time consumer video applications over optical networks. The work in [20] described the architecture of High Performance Digital Media Network (HPDMnet) [35], which is a global experimental end-to-end network that can support high resolution imaging, 3D movies, and 4/8K streams. The test-bed was used for many-to-many streaming where each site was sending 1.5 Gbps stream and receiving two such streams from the other sites over geographically distributed locations. The network used IP addressing but the paths avoided routers to ensure high performance and quality. HPDMnet also used jumbo frames (approximately 9000 Bytes) as with normal Ethernet packet payload does not adequately support long duration flows. An architecture based on HPDMnet is also described for real-time video applications. Wavelength division multiplexing (WDM) is a data transmission technology which multiplexes a number of optical carrier signals onto a single optical fibre by using different wavelengths of laser light.

The paper described optical transmission and switching techniques including OBS, optical circuit-switched, WDM networks, OTDM, and the conditions favouring their use. The content adaptation, that is, different formats, resolution, and frame rates, of multimedia content to suit an end device can take place at the server, receiver, or large cluster facilities.

4.7. Cloud Based Services. The advantages of utilizing a cloud based service are that the computing and storage resources can be elastically mustered as required and released when no longer needed. This model fits well with the requirements of digital cinema where the requirements of service delivery are periodic and known in advance.

A cloud based architecture, Advanced Media Services Cloud (AMSC), is proposed in [21] to support the digital cinema applications over optical networks. The architecture provides on-demand network, processing, and storage resources to users. A mathematical model based on graph theory is presented to cater for the adaptive and nonadaptive requirements. The Integer Linear Programs (ILP) models are evaluated through simulating an optical distribution network. It considered compressed HD, 4K, and 8K formats. It was shown that as the requests for UHD content increase there is a drop in meeting the requests through graceful degradation. The proposed architecture was deemed good for applications where the streaming requests are known in advance.

4.8. Multiple Channels. Through limiting the interferences in multiple wavelength optic fibre, [22] demonstrated the transmission of aggregate 32 Tbps of data over 320 separate optical channels (with 25 GHz spacing) on a single, 580 mile optic fibre. The link is comprised of seven spans, each with Erbium-doped fibre amplifier (EDFA) and a section of a low loss optical fibre. The researchers contended that in view of the growth in IP traffic such research efforts to increase the fibre optic capacity are vital for a sustained growth.

4.9. Implementations and Demonstrations. In [18], trial of distributing Hollywood movies in digital format (4K) via a network to theatres in Japan was tested. The overall aim of the project was to verify the DCI specifications from distribution to exhibition. It was the world's first attempt at network distribution of DCI compliant digital cinema to multiple movie theatres in movies distributed from Hollywood. The trial continued for one year involving partners from both USA and Japan to test distribution, screening, encryption, and key management. The optical networks were used for distribution of movies from distribution centres to the theatres verifying the complete digital cinematography work flow.

A demonstration at first annual US Ignite Application Summit in Chicago streamed UHD 3D movies in 4K resolution over high performance optical networks [23]. The research emphasized use of software rather than hardware for content distribution in future. The demonstrations used the developed open source software for high performance networks; UltraGrid (video and audio streaming software) was used to stream uncompressed movies from Poland to the US and Scalable Adaptive Graphics Environment (SAGE) for storing very large data files at the source, dispensing the need to replicate content at many locations. The optical fibre infrastructure of Global Lambda Integrated Facility (GLIF) consortium provided a 10 Gbps network path for this event whereas average data rate was 3.4 Gbps over approximately 10,000 km fibre length.

5. Technological Innovations Supporting Digital Cinema

Recent major advances in optical networking include the deployment of high speed optical connections from core networks to enterprise and residential users ensuring dramatic increase in optical signal speed and reach. The improvement in control and management planes support increasingly diverse types of traffic and services supporting high resolution, high-quality, real-time consumer-driven media production and distribution.

5.1. Optical Switches. All-optical buffers will likely be the key element to facilitate future all-optical networks. Many applications would benefit from such a novel function, such as packet synchronization, label processing, and contention management. Applications requiring variable delays can be accommodated by recirculating fibre-loop based optical memory and Semiconductor Optical Amplifier (SOA) for dynamic power adjustment [36].

5.2. Modern Laser. Researchers have experimented with lasers to create giant displays enabling screening of 3D content [37] which does not need 3D glasses. By sending laser beams into different directions, different pictures are visible from different angles creating a 3D effect. The system can even work outdoors with bright light. The system is currently experimental but promising and can present hundreds of pictures rather than just two in 3D. The laser projectors [38] can render 4K resolution 3D movie content on 32.8 ft wide cinema screens.

Further, the introduction of wavelength tuneable lasers that are capable of tuning to any channel on the International Telecommunications Union (ITU) grid with switching speed in ns [39] will dramatically reduce the cost of running system through sparing functions, allowing system operators to reduce laser inventory, replacing fixed wavelength lasers with wavelength tuneable lasers.

5.3. Forward Error Correction (FEC). At higher frame resolutions, like UHD, the effects of losses in the video data become easily perceptible and result in a low quality user experience. FEC schemes [40] like Fountain Codes favour the cloud based/CDN deployments [41] where the content can then be downloaded from multiple sources and combined at the destination. FEC based on LDGM codes were proposed in [3] for error protection of video streams providing good results.

5.4. Multicore Fibres. Multicore Fibre (MCF) is a new revolutionary approach to engineer a fibre for high capacity applications, using spatial-division multiplexing that splits the signals among several separate cores in the same fibre. MCF has become a hot topic recently as developers look for new ways to increase fibre capacity and to keep packaging costs sustainable. Sakaguchi and colleagues [42] from Sumitomo Electric's R&D Lab (Yokohama, Japan) and Optoquest (Saitama, Japan) described WDM of 10 Gbps signals in seven-core fibres during the regular sessions. Recently another research group [43] successfully demonstrated 51.1-Tbit/s MCF transmission over 2520 km using cladding-pumped seven-core EDFAs with 73 $*$ 100 Nyquist pulse shaped DP-QPSK signal per core.

5.5. Reconfigurable Optical Add/Drop Multiplexers (ROADM). Fast reconfigurable ROADMs have been reported with integrated optical label readers and channel selectors [20]. The concept of flexible add-drop bandwidth has also been used in ROADMs and wavelength selective switches with liquid-crystal-on-silicon (LCOS) technologies [23, 44]. New ROADMs make use of LCOS arrays that can give very fine spectral resolution (1 GHz) and allow a wide range of add-drop spectral shapes, which is especially beneficial for UHD media services. In addition, field-programmable gate array (FPGA) technologies for optical transmitters and receivers have advanced, being able to produce line rates at 100 Gbps speeds, thus enabling a true real-time digital signal processing [20].

5.6. Modulation/Multiplexing. A major challenge to increase bandwidth in optical telecommunications is to encode electronic signals onto a light wave carrier by modulating the light at very high rates. Polymer electrooptic materials have the necessary properties to function in photonic devices beyond the 40 GHz bandwidth currently available [45].

Researchers have explored (and close to maximally exploited) every available degree of freedom, and even commercial systems now utilize multiplexing in time, wavelength, polarization, and phase to feed/speed more information through the fibre infrastructure. A team from Verizon (Richardson, TX) and NEC Labs (Princeton, NJ) described mixing 100 Gbps optical channels with "superchannels" transmitting 450 Gbps and 1.15 Tbps across wider spectral regions through 3560 km of fibre in the Verizon network [46]. The superchannels combined orthogonal frequency division multiplexing (OFDM) with dual-polarization quadrature phase-shift key (DP-QPSK) modulation of multiple subcarriers within the transmission band.

5.7. Photonic Integrated Circuits. Modern Photonic Integrated Circuits (PIC) allow cost reduction through Monolithic Integration [47]. These devices are ideal building blocks for the development of next generation, efficient, high bandwidth fibre optic networks to run SHD/UHD video applications. Advances have been driven by economics, as well as the need for greater capacity and scalability. Inflection points in this evolution have typically occurred when technological breakthroughs have enabled a paradigm shift that allowed significant cost reductions or new, advanced capabilities, or both.

5.8. Self-Organised Network Management. It is important to explore the latest advancements in network management like Automatic Deployment of Services, Software Defined Networking (SDN), Network Function Virtualisation (NFV), Cloud Computing, and other technologies in virtualised 5G network environments. One such effort is the project SELFNET: "Framework for Self-Organised Network Management in Virtualized and Software Defined Networks" (H2020-ICT-2014-2/671672) [48]. The project aims to find novel solutions for optimising the management of real-time video applications based on latest and emerging video standards and related technologies.

5.9. Elastic Optical Networks. Elastic optical networking (EON) improves infrastructure utilization by implementing flexible spectrum allocation with small spectrum slots instead of fixed 50 GHz grid dense wavelength division multiplexing solution [49, 50]. The key objectives of EON are achieved in the Project: IDEALIST, "Industry-Driven Elastic and Adaptive Lambda Infrastructure for Service and Transport Networks" (EUR 12 515 004, ICT-2011.1.1, Future Networks) [49, 51].

This new EON flexible grid also supports sliceable bandwidth variable transponder (SBVT) which can provide even higher levels of elasticity and efficiency to the network while reducing cost of 400 Gbps and 1 Tbps SBVTs by at least 50% and saving of IP ports [49].

Another group working on the same project experimentally tested the multidomain multivendor EONs by using interoperable SBVTs, a GMPLS/Border Gateway Protocol-Link State (BGP-LS) based control plane, and a planning tool. They achieved error-free transmission up to 300 km with hard-decision and soft-decision FEC using only the information distributed by the control plane [50, 51].

6. Conclusion

A comprehensive survey of the optical network technologies for digital cinema has been presented highlighting the implications of emerging optical technologies in bringing further improvements to the existing digital cinema content transmission. The optical communications technology would foster the transformation of the cinema industry into an all-digital immersive experience. This transformation will bring about disruptive changes to the cinematography work flow with more advanced acquisition and editing processes, video compression, communication, and transport mechanisms being deployed. The cloud based optical network architecture would enable a fully integrated global content distribution network for rich multimedia applications integrated seamlessly for home screening, broadcasting, and mobile viewing.

The future may bring the digital content migration from an intraonly (frame by frame) compression to exploiting interframe compression. The infrastructure will enable further advancements as the availability of high speed networks coupled with an unprecedented increase in multimedia communications from mobile and other capture devices will create both opportunities and challenges. The affordability of digital content generation and distribution will encourage new entrants to a previously restricted and specialized domain, ultimately bringing the art of movie-making into the public domain.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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